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Aluminum Sign Corrosion Investigation

FINAL REPORT



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16. Abstract This report contains the findings of an investigation undertaken to determine the cause(s) of corrosion of aluminum highway signs mounted on ACQ treated wooden sign posts. Various installations from different parts of the state were experiencing premature and severe corrosion leading to complete failure around the mounting hardware causing the signs to fall off the posts they were attached to. Thus, samples of new and corroded signs were sent to a private laboratory for more in-depth testing. In addition, a literature search was conducted that focused on the new wood preservatives being used as a result of the EPA's ban on chromated copper arsenate (CCA) treated lumber. WisDOT recently stopped using the CCA treated posts and has since been using alkaline copper quaternary (ACQ) treated wooden sign posts, thus the reason for the literature search. It was discovered that the new wood preservatives contain approximately 3 times the amount of copper as compared to the CCA treated lumber. As a result the copper leaches out of the wooden sign posts and reacts with the aluminum signs causing the corrosion. Thus, the major recommendation of this report is to apply some kind of rubberized backing to the signs. Secondly, it is recommended that the specifications for the mounting hardware be changed to require hot dip galvanized hardware with a minimum of five (5) mils protective coating.			
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WisDOT Highway Research Study # WI-04-02

By

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For

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DIVISION OF TRANSPORTATION INFRASTRUCTURE DEVELOPMENT
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INTRODUCTION

This report contains the findings of an investigation into the corrosion of Type II aluminum highway signs. Various installations from different parts of the state were experiencing premature and severe corrosion leading to complete failure around the mounting hardware causing some signs to fall off the treated wooden posts they were attached to. Since this was not an ideal situation, samples of the sign materials and mounting hardware were sent to a private laboratory for in-depth testing and analysis in an effort to get a definitive reason for the corrosion distress. In addition, a comprehensive literature search was conducted on the new wood preservative formulations that went into effect as of January 1, 2004. This report contains the findings of those efforts and recommendations to address the problems being encountered in the field.

BACKGROUND INFORMATION

In this case the distress or corrosion appeared to originate around the galvanized lag bolts and spread out from there. The photographs below show the distress that is occurring.



These photographs show the backside of a sign that was installed 8-20-02 on an Alkaline Copper Quaternary (ACQ) treated wooden post. The sign fell off the post around mid-March 2004 after less than 2 years in service.



These photographs show another sign mounted on an ACQ post that was in service for approximately 15 months.

Galvanic Corrosion Overview

Galvanic corrosion occurs when dissimilar metals are in contact with each other in the presence of an electrolyte (a liquid medium). The *degree* of corrosion is dependant on many various factors. Some of the more relevant ones in this case include salt (deicers), presence of water (rain, snow, dew, capillary water), ground contact, chemical makeup and retention levels of chemicals used for wood preservatives, moisture content of wood, atmosphere, and the presence of other metals such as galvanized lag bolts in this case.

Wood Preservatives Review

As of January 1, 2004, the Environmental Protection Agency (EPA) has banned Chromated Copper Arsenate (CCA) for residential construction applications where people and pets may come in contact with treated wood surfaces due to the carcinogenic nature of the arsenic used in the CCA wood treatment. (Note: However, under this ruling, the EPA has exempted certain agencies and applications of CCA treated lumber. Wood used in highway construction is mentioned in the filing and thus exempt from the ban.) As a result of the EPA action and worker health risks, WisDOT switched from using the CCA treated posts and started using the Alkaline Copper Quaternary (ACQ) treated posts.

The new ACQ posts have approximately three times more copper than the old CCA posts and as a result are more corrosive to metal materials used in conjunction with the treated wood, especially aluminum as was discovered from the literature search. Chromated Copper Arsenate (CCA) exists in several formulations or types but contains approximately 65% Chromium, 18% Copper and 16% Arsenate. Alkaline Copper Quaternary (ACQ) on the other hand contains approximately 67% copper, and 33% didecyldimethylammonium chloride (DDAC). Copper Azole type A (CA-A) contains 49% copper, 49% boric acid, and 2% tebuconazole, while Copper Azole type B (CA-B) contains 96% copper and 4% tebuconazole. Wood treated with Borate Oxide (borates) is not recommended for direct ground/water contact since the preservative treatment will leach out of the wood in the presence of water.

LAB ANALYSIS RESULTS

As previously mentioned, samples of new and corroded signs were sent to a laboratory for testing and analysis of the signs' microstructure and corrosion products. As suspected, the principal conclusion suggested that copper from the ACQ treated signposts reacted with the aluminum signs and caused the corrosion, as copper was detected in the corrosion products. Secondly, newer sign stock showed more porosity in the microstructure, thus suggesting that those signs were more prone to corrosion as compared to a sample of older sign stock. Recommendations included that WisDOT look at alternative wood preservative treatments for the signposts that would restore the copper levels back to those found in the CCA treated posts, however that is not an option due to the alternatives available and WisDOT's desire to move away from the use of CCA treated posts. The other major recommendation was to put a protective coating on the back of the signs that would be polymeric in nature. In addition, it was suggested that the quality of the wrought aluminum used in the signs should be reviewed for the presence of porosity. "The increased porosity found in the interior of the newer vintage material represents a decline in the quality of the material when compared to the older vintage sample." The full report can be found in Appendix B.

MISCELLANEOUS

The life expectancy of aluminum signs is approximately 10 years with many signs not replaced until around year 15. This is relevant in that any solutions for this problem should last at least that long.

The results of the lab testing that was done on a sample lag screw showed that the zinc coating was only 0.16 mils thick. This really does not offer much protection and in fact it was learned that some lag screws were rusting in the bins in the shops prior to even being installed in the field. After conferring with Craig Wehrle, WisDOT Bridge Metals and Fabrication Engineer, he suggested that hot-dipped galvanized mounting hardware with a minimum of five (5) mils of protective coating be used exclusively in lieu of electro-galvanized, mechanically galvanized or cadmium plated hardware which were all options in WisDOT specifications at the time.

In a related matter, there did not appear to be much control over selection and use of mounting hardware. It was learned that for one shop anyways, an outside supplier restocks the hardware bins as “they see fit”. Steps may need to be taken to ensure the proper selection and use of the proper graded galvanized hardware.

It was noticed that newer and older vintage signs had a different tint to them, indicating a possible difference in the type of coating and or the thickness of the coating. The newer vintage signs have more of a copper colored tint to them. Thus the question arose regarding the anodizing of the aluminum signs and if there was a problem with that process. Anodizing is basically an electro-chemical process that coats the aluminum sign blanks as a way to provide durability and protection from the elements (sun, salt, water, oxidation/rust). The lab testing did indeed determine that the older vintage sign blanks were of better quality than the newer vintage sign blanks with the new vintage sign blanks exhibiting more porosity in the microstructure which would result in increased susceptibility to corrosion.

During the course of the investigation it was learned that WisDOT is considering hydro-stripping used signs as a way to save money on new sign blanks. This process could affect the protective anodized coating by increasing the vulnerability of the signs to oxidation and salt spray from

winter plowing activities, and as such, any such deleterious ramifications should be thoroughly investigated before moving forward with this process.

CONCLUSIONS

1. Aluminum highway signs mounted on ACQ treated wooden posts have corroded and fallen off the posts in as little as fifteen months due primarily to the copper in the ACQ posts reacting with the aluminum signs. The ACQ treated posts contain approximately three times the amount of copper as compared to the old CCA treated posts.
2. Newer vintage signs have more porosity in the microstructure of the signs as compared with the older vintage signs. This results in an increased susceptibility to corrosion.
3. Current specifications for mounting hardware are no longer adequate given the switch from CCA treated posts to ACQ treated posts.

RECOMMENDATIONS

1. The major recommendation here is to apply a protective barrier between the aluminum signs and the ACQ treated wooden posts. It is recommended that a rubber spray or a rain/ice/weather shield type of barrier be used on the backside of the signs and that the barrier be applied to the entire backside of the signs so that snow accumulation in the winter does not cause the copper in the treated posts to leach out and come in direct contact with the back of the aluminum signs.
2. It is recommended that the specification for the mounting hardware be changed to require hot-dipped galvanized hardware with a minimum of five (5) mils of protective coating as per WisDOT's Bridge Metals and Fabrication staff.
3. It is recommended that the anodizing specification be updated or reviewed to ensure the signs have adequate microstructure and protection from the effects of the elements, i.e. salt, sun, oxidation, etc.
4. It is recommended that steps be taken in the various district/county sign shops to ensure the proper selection and use of the proper graded galvanized mounting hardware.

5. It is recommended that future hydro-stripping of used sign blanks be thoroughly investigated for any deleterious ramifications such as removing the protective anodized coating prior to moving forward with this process on a large scale.
6. It is recommended that the signposts be stored in such a way to promote air circulation around the stockpile of posts in an effort to reduce the amount of moisture in the posts.
7. It is recommended that Signing and Marking perform life cycle cost analysis of metal signposts vs. the ACQ treated wooden signposts.

APPENDIX A

(Original RED Submittal)

REPORT ON EARLY DISTRESS (RED) IN HIGHWAYS AND BRIDGES

3502 Location of Apparent Distress:
Highway: Various E W S N Date Constructed:
Project ID: 0653-31-10 City / Village:
Bridge ID: County: Various
Project Begin / End:
Other Location Info: (Distance, Direction, Reference Point, Intersection, Landmark, etc.)

Various installations of Type II aluminum highway signs.

2. Highway / Bridge Element where Distress Appears: (x)

Highway: ☐ Pavement ☐ Shoulder ☐ Embankment ☐ Drainage ☒ Marking/Signing ☐ Hardware

Bridge: ☐ Deck ☐ Railing ☐ Expansion Joint ☐ Substructure ☐ Other

Explanation:

There have been several cases brought forward where Type II aluminum signs are failing prematurely (some within 12 months) because of sheet aluminum corrosion (See attached photographs)

3. Probable Cause of Distress:

There are most likely two probable causes of distress. The first could be galvanic reaction between the sheet aluminum and mounting hardware caused by aluminum and/or hardware not meeting coating specifications. The second probable cause could be the new ACQ wood post treatment. WisDOT has moved away from the CCA post treatment.

4. Recommended Action / Correction (How would you handle it?):

We need to have an analysis performed as to what “chemically” is happening. Once we have this analysis, then we can proceed on the correct plan/path to correct it. This “plan/path” could be switching wood post treatment; aluminum blank treatment or finding the vendor is not supplying aluminum according to specifications. In a 01/22/04 meeting between Pete Kemp, Joe Wilson, Ned Schmitt and Matt Rauch, it was determined the best course of action would be to first clearly define what the problem is, then proceed with correction of the problem.

5. Report Submitted by: Matthew R. Rauch, P.E. Telephone # (608) 266-0150

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APPENDIX B

(Lab Analysis Report)

Report on the Evaluation of Corrosion in Aluminum Signs

Description and Scope of Work

Five road signs produced from an aluminum alloy identified as 5052-H38 were submitted along with several lag screws. The screws are reportedly used to secure the signs against pressure-treated wooden posts. Three of the signs, which were reportedly manufactured from a recent vintage of aluminum sheet stock, exhibited severe corrosion after a short time in service. A new sign from the same time period was provided for comparison along with a new sign from a prior vintage, which is representative of a more corrosion-resistant material. It was indicated that changes were made to the compounds used to treat the wood posts. Specifically, a previous treatment designated as chromated copper arsenic (CCA) had been replaced by an ammonia copper quaternary (ACQ). This latter compound would have increased the concentration of copper. The nature and likely cause of the corrosion were investigated and comparative studies were conducted comparing the older and newer vintage sign materials with regard to surface appearance and microstructure. In addition, a typical new lag screw was evaluated for plating type and plating thickness. No specification requirements were provided for the sign or the lag screw materials. The components are identified in this report as follows:

Table 1 – Legend of Sample Description

Sample	Description
1	New sign; old vintage
2	New sign; new vintage
3	Corroded sign; new vintage
4	Corroded sign; new vintage
5	Corroded sign; new vintage
6	Lag screw; new

Tests and Results

Sample 1 is shown as received in Figure 1, with the region that was identified for metallographic study indicated by the blue line in the view. Higher magnification views of a typical area on the surface of Sample 1 are shown in Figures 2 and 3. Parallel grooves are evident, which is consistent with rolled aluminum sheet material. Sample 2 is shown as received in Figure 4 with a similar identifying blue line to mark the area examined. Higher magnification views of the surface are provided in Figures 5 and 6. The parallel grooves are apparent in this material as well, however scattered local discoloration is also evident.

Sample 3 is shown as received in Figure 7, where severe localized corrosion is evident around the lag screw holes. A typical corroded area is shown at higher magnification in Figure 8, where white aluminum corrosion by-products are evident along with a small amount of red rust bleedout adjacent to the edge of the hole. The red rust is likely to arise from corrosion of the adjacent lag screw. A higher magnification view in the vicinity of the corroded area of Sample 3 is shown in Figure 9. In this image relatively non-corroded and corroded regions are both present. Higher magnification views of these two regions are shown in Figures 10 and 11, respectively. The non-corroded regions exhibit parallel grooves and scratches with few surface deposits. The corroded area displays extensive white corrosion deposits. Sample 4 is shown as received in Figure 12. As in Sample 3, localized corrosion is present adjacent to the lag screw holes. A higher magnification view showing a typical corroded area is provided in Figure 13, where aluminum corrosion by-products are present along with the red rust bleedout.

Sample 5 is shown as received in Figure 14. Severe corrosion is evident here that had resulted in the separation of the mating half of the sign. A higher magnification view of the corroded area is provided in Figure 15. This area shows features that are generally consistent with exfoliation corrosion in wrought aluminum. Typical new lag screws are shown as received in Figure 16. All four parts exhibit a shiny silver appearance, which is characteristic of zinc-coated or cadmium-coated components. The lag screw at the left hand side of Figure 16 was designated as Sample 6, and the region of this part identified with the blue line was selected for metallographic study.

The surfaces of sign Samples 1, 2, and 3, and the surface of lag screw Sample 6, were studied further using scanning electron microscopy (SEM) equipped with an energy dispersive x-ray spectrometer (EDS) to provide an elemental profile of the samples. EDS will detect and quantify elements from atomic number 5 (boron) and higher. Relative percentages of the detected elements are reported and the detection limit of the technique is 0.1%.

An SEM image of a typical area of Sample 1 is shown in Figure 17 and higher magnification images are provided in Figures 18 and 19. This area exhibits parallel grooves and some scratches. Figure 20 shows an SEM image of the surface on Sample 2. The parallel grooves are again evident along with localized light and dark areas, noted in Figure 21 with the designations 'L' and 'D', respectively. These regions are shown at higher magnification in Figures 22 and 23, respectively. EDS analysis was conducted on the surface and a freshly scraped area of the base metal in Sample 1. This analysis was also performed on both the light and dark surfaces of Sample 2 along with a scraped area of the base metal. The results of these tests appear in Table 2. The actual EDS spectra are also provided.

Table 2 – EDS Results for Sample 1 and 2
(All Values in Relative Weight Percent)

Element	Sample 1		Sample 2		
	Base Metal	Surface	Base Metal	Location L	Location D
Iron	0.3	0.1	0.3	0.6	0.3
Chromium	0.2	0.3	-	1.1	0.6
Silicon	-	-	-	2.5	1.3
Aluminum	97.0	84.7	97.3	72.2	81.1
Magnesium	2.5	2.1	2.4	1.6	1.7
Carbon	-	6.7	-	6.3	5.1
Oxygen	-	6.1	-	15.7	9.9

The base metal of Sample 1 is comprised of aluminum and magnesium with low levels of iron and chromium. These results are consistent with a 5000-series aluminum alloy. The surface was found to contain the base elements along with carbon and oxygen. The carbon and oxygen may be from trace amounts of organic deposits. The base metal of Sample 2 shows comparable composition to that of Sample 1. The light and dark regions both contain, in addition to the base metal elements, substantial amounts of carbon and oxygen and smaller amounts of silicon and chromium. These again suggest the presence of organic debris and some mineral-based deposits. The chromium observed in the light and dark regions is likely to be present in the base metal as well, but may be below 0.1% and therefore undetectable by this technique.

An SEM image showing a discolored region of Sample 3 is provided in Figure 24. Localized adherent deposits were found in this area. A relatively clean area was identified in Location A while Location B shows the deposits. Higher magnification views at Location A are shown in Figures 25 and 26 and parallel grooves, scratches, and some localized deposits can be seen. Similar views at Location B are provided in Figures 27 and 28. In this region, adherent amorphous deposits and corrosion products are evident. Two additional heavily corroded regions from Sample 3 were also imaged by SEM. Location C is

shown in Figures 29-31 and Location D is presented in Figures 32-34. These regions also contain amorphous corrosion deposits. EDS analysis was performed on all four locations and the results are provided in Table 3 along with a result from the base metal. The actual spectra are also provided.

Table 3 – EDS Results from Sample 3

Element	Base Metal	Location A	Location B	Location C	Location D
Iron	0.3	0.4	0.3	0.3	0.1
Manganese	-	0.1	-	-	-
Chromium	0.2	0.4	0.1	-	-
Silicon	-	0.7	0.2	-	-
Aluminum	97.2	75.7	30.7	31.8	32.6
Sodium	-	-	1.2	-	-
Magnesium	2.3	1.8	1.0	-	0.7
Calcium	-	-	0.3	-	0.1
Copper	-	0.2	1.3	0.3	1.2
Zinc	-	-	0.7	-	-
Chlorine	-	-	-	0.5	-
Carbon	-	9.0	5.2	4.1	3.8
Oxygen	-	11.7	59.0	63.0	61.5

In addition to the base metal elements, Location A exhibits levels of carbon and oxygen comparable to those observed on the surfaces of Samples 1 and 2. These are likely associated with organic debris and possibly some oxidation products. In addition, Location A shows low levels of manganese, silicon and copper. The other three locations show very high levels of oxygen and much reduced percentages of aluminum. This shows evidence of significant oxidation. Some carbon is also present as organic or partially organic debris. Copper appears in all of these areas and may be the result of direct contact with the copper compounds in the treated wood. Location B also shows traces of silicon, sodium, calcium, and zinc. These may represent by-products from mineral-based deposits. Location C shows the presence of chlorine, probably present in the form of chlorides. Chlorides are known to be corrosive to aluminum alloys under aqueous and mildly acidic conditions. The composition of Location D is very similar to that of Location B.

EDS analysis was also performed on the surface of the lag screw identified as Sample 6 and a freshly ground area of the base metal. These results appear in Table 4 and also shown in the actual spectra. This analysis showed the base metal to be composed of iron and manganese while the surface contained primarily zinc along with some iron, chromium, sulfur, carbon and oxygen. This is consistent with a zinc and dichromate coating and may also indicate the presence of trace organic deposits.

Table 4 – EDS Results for Lag Screw
(All Values in Relative Weight Percent)

Element	Base Metal	Surface
Iron	99.6	1.8
Manganese	0.4	-
Chromium	-	0.3
Zinc	-	89.6
Sulfur	-	0.1
Carbon	-	3.0
Oxygen	-	5.2

Transverse metallographic cross sections were prepared through sign Samples 1, 2, and 3 and through the lag screw Sample 6. The regions evaluated are indicated by the blue lines marked on Figures 1, 4, 7, and 16, respectively. The cross section through Sample 1, which is representative of the older vintage material, is shown in Figure 35. A small amount of porosity is observed in the core section. Figures 36 and 37 show higher magnification views of the unetched cross section also show this limited porosity along with iron/chromium rich phases in the core. An etched region is shown in Figure 38. After etching magnesium silicide particles were found to be evenly distributed with the iron/chromium rich phases.

The cross section through Sample 2 is shown in Figure 39 and reveals a much higher level of porosity. Figure 40 shows a 100X magnification of this cross section revealing both the porosity and the iron/chromium rich phases. Figures 41 and 42 provide 500X views of the sample unetched and etched, respectively. These images show the higher degree of porosity and the more scattered arrangement of magnesium silicide particles. The cross section through Sample 3 is shown prior to etching in Figure 43. Severe porosity is evident within the core similar to that observed in Sample 2. In Sample 3 corrosion was also noted along the surface and a typical corroded area is shown in Figure 44. The features in this area are consistent with the severe corrosion of wrought aluminum. The microstructure of this region is shown unetched and etched in Figures 45 and 46, respectively. Here again both magnesium silicide and iron/chromium rich regions are evident. The surface profile of the lag screw Sample 6 is shown in Figure 47. A zinc layer is evident along the surface with an approximate nominal thickness of 0.16 mils.

Conclusions

The results of this study show that deterioration had occurred in the newer vintage aluminum signs due to crevice corrosion at the lag screw joints. Some copper was detected within the corrosion products, which may have leached out from the wooden posts treated with the ACQ material. Copper and copper compounds are known to reduce the corrosion resistance of aluminum and aluminum alloys and can actually cause this corrosion. Direct contact between aluminum and copper sets up a galvanic process that can be accelerated by the presence of moisture and other polar by-products and debris such as salts. The elemental composition of the newer vintage sign material shows surface deposits that represent a significant level of oxidation in the aluminum. In addition, the newer vintage aluminum sign contains a much higher level of porosity, which also reduces corrosion resistance. This suggests that the corrosion occurs more rapidly in the newer vintage material due to a combination of porous microstructure and the presence of copper in direct contact with the aluminum.

Recommendations

A treatment for the wood post should be sought that returns the copper levels to those in the original CCA treatment. Alternately, a protective coating may be applied to the aluminum sign material to provide a barrier between the wood and the aluminum. This would most likely be a polymeric system. Assistance can be provided in evaluating various candidate pressure treating systems and coating materials, if necessary. In addition, the quality of the wrought aluminum used in the signs should be reviewed for the presence of porosity. The increased porosity found in the interior of the newer vintage material represents a decline in the quality of the material when compared to the older vintage sample.

Michael Sepe, 5/22/2004



Figure 1
The older Vintage Sign, identified as Sample 1, is shown as-received with the region that was identified for metallographic study indicated by the blue line

Figure 2
Higher magnification view of the surface of Sample 1, showing the parallel grooves (Approx. 14X)

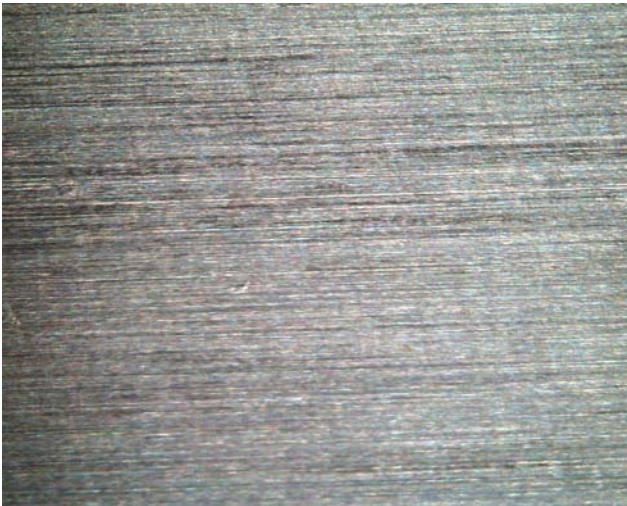


Figure 3
Higher Magnification view at the center of Figure 2, showing parallel grooves (Approx. 35X)

Figure 4
The newer vintage sign, identified as Sample 2, is shown as-received with the region that was identified for metallographic study indicated by the blue line.





Figure 5
Higher magnification view of Sample 2, showing parallel grooves and discolored areas (Approx. 14X)



Figure 6
Higher magnification view at the center of Figure 5, showing parallel grooves and discolored areas (Approx. 35X)

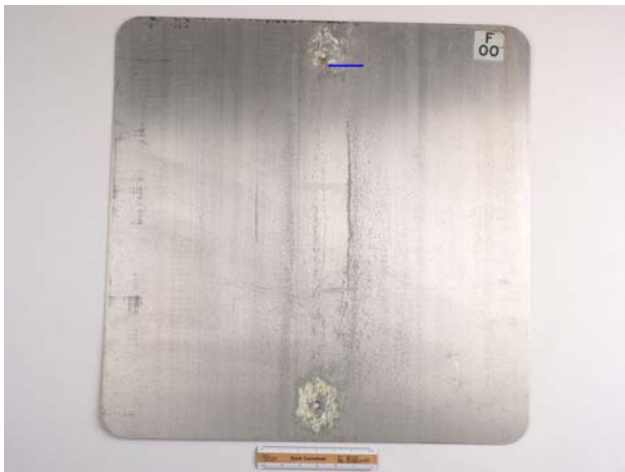


Figure 7
The corroded sign, identified as Sample 3, is shown as-received. Localized corrosion is evident around the lag screw holes. The area that was identified for metallographic study is indicated by the blue line.



Figure 8
Higher magnification view of a typical corroded area of Sample 3. White corrosion deposits are evident along with some red rust bleedout. (Approx. 1.4X)



Figure 9
Higher magnification view within the corroded region of Sample 3, showing relatively clean and corroded areas on the surface (Approx. 14X)



Figure 10
Higher magnification view within a typical relatively clean area of Sample 3, showing parallel grooves and scratches, with some adherent deposits. (Approx. 35X)



Figure 11
A typical corroded region of Sample 3 exhibits adherent aluminum corrosion products (Approx. 35X).

Figure 12
The corroded sign, identified as Sample 4, is shown as-received, where localized corrosion is evident around the lag screw holes.





Figure 13
Higher magnification view of a typical corroded area of Sample 4, showing aluminum corrosion products and red rust bleedout (Approx. 1.4X)

Figure 14
The corroded sign section, identified as Sample 5, is shown as-received. Severe corrosion has resulted in separation of the matting half of the sign

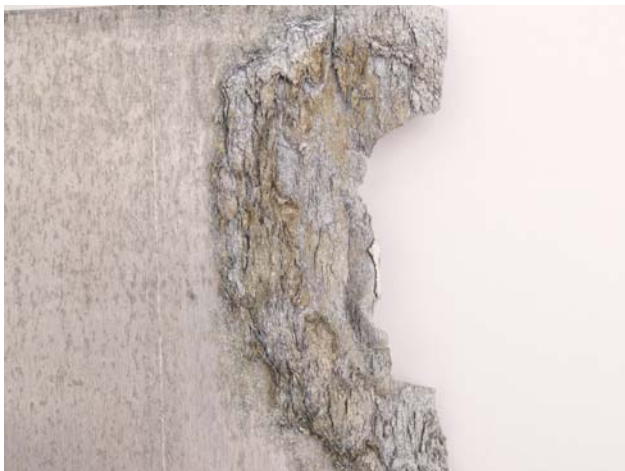


Figure 15
Higher magnification view within a typical corroded area of Sample 5, showing visual features that are generally consistent with exfoliation in wrought aluminum. (Approx. 1X)

Figure 16
Typical new lag screws are shown as-received. The lag screw at the left was identified as Sample 6, and the region that was selected for metallographic study is indicated by the blue line.





Figure 17
Scanning Electron Micrograph showing a typical area on the surface of Sample 1. This area exhibits parallel grooves in the surface (SEM 50X)

Figure 18
Higher magnification view at the center of Figure 17, showing parallel grooves and scratches. (SEM 200X)

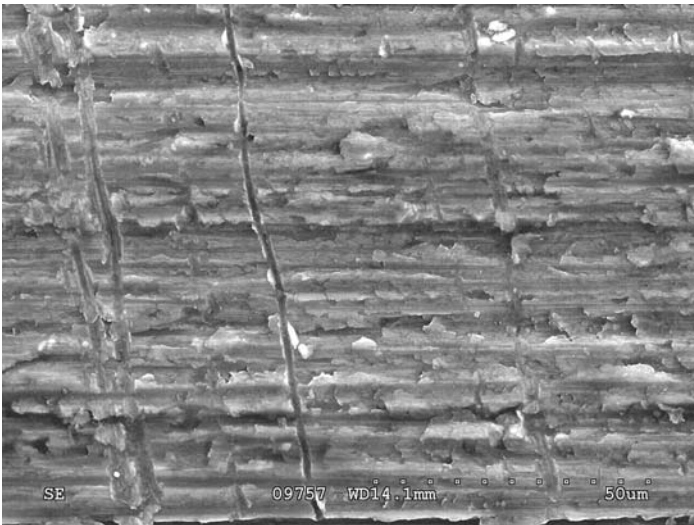


Figure 20
Scanning electron micrograph showing a typical area on the surface of Sample 2, where localized relatively light and dark regions are evident, along with parallel grooves. (SEM 50X)

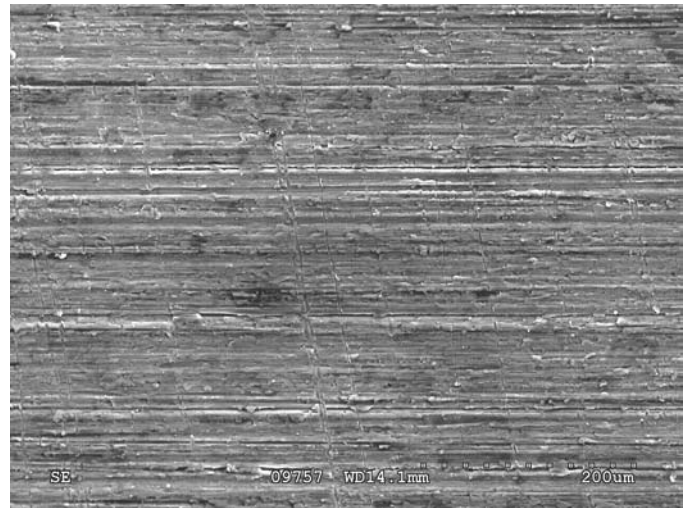


Figure 19
Higher magnification view at the center of Figure 18, showing the parallel grooves and scratches. (SEM 1000X)



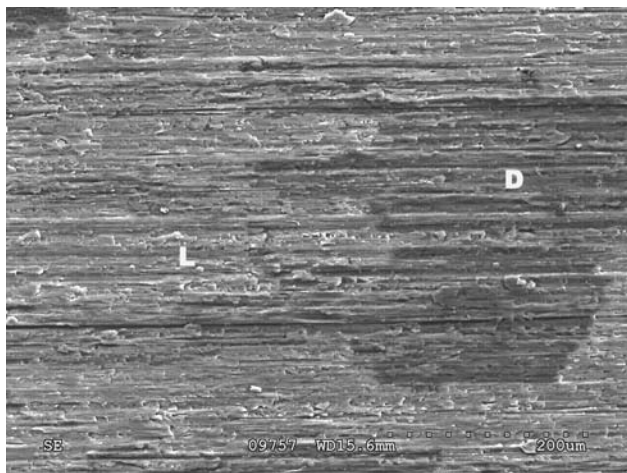


Figure 21
Higher magnification view at the center of Figure 20, showing parallel grooves with relatively light and dark areas. The relatively light area was identified as Location L, and the relatively dark area was identified as Location D. (SEM 200X)

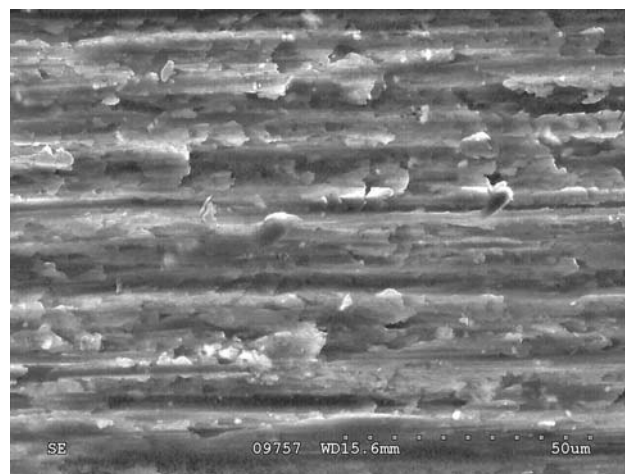


Figure 22
Higher magnification view at Location L, as illustrated in Figure 21. Parallel grooves are evident in this area. (SEM 1000X)

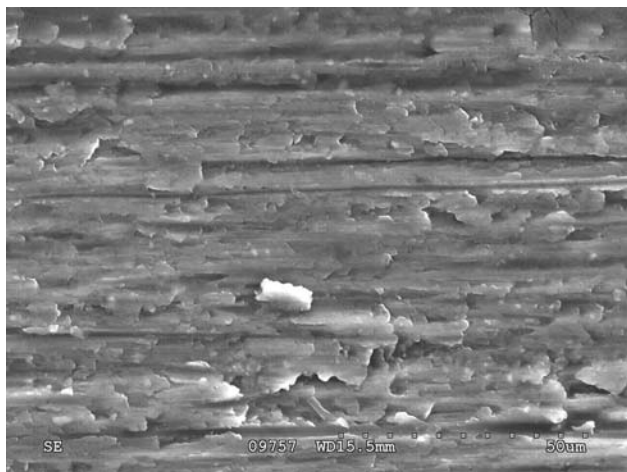
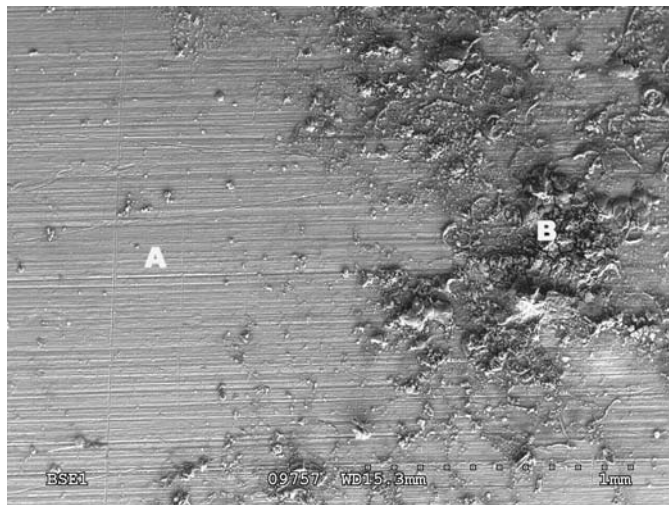


Figure 23
Higher magnification view at Location D, as illustrated in Figure 21. Parallel grooves are evident in this area. (SEM 1000X)

Figure 24
Scanning electron micrograph showing the surface of Sample 3, in the vicinity of the corroded area. Relatively clean and corroded regions were identified for further study at Location A and B, as shown. Adherent deposits are evident at Location B. (SEM 50X)



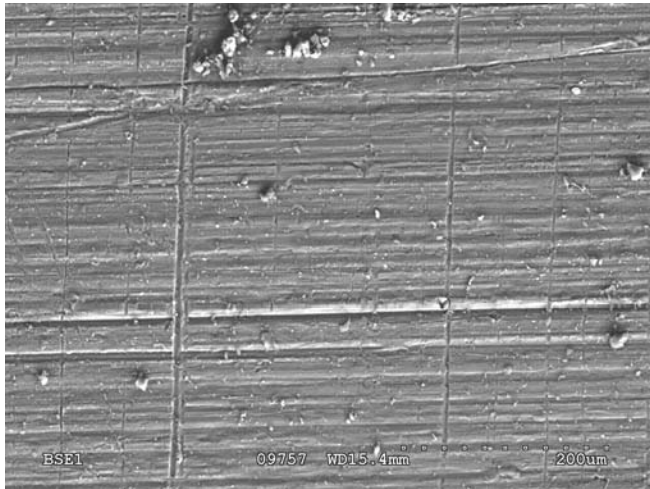


Figure 25
Higher magnification view at Location A, as illustrated in Figure 24, showing parallel grooves and scratches, with some adherent deposits. (SEM 200X)

Figure 26
Higher magnification view at the center of Figure 25, showing grooves, scratches, and adherent deposits. (SEM 1000X)

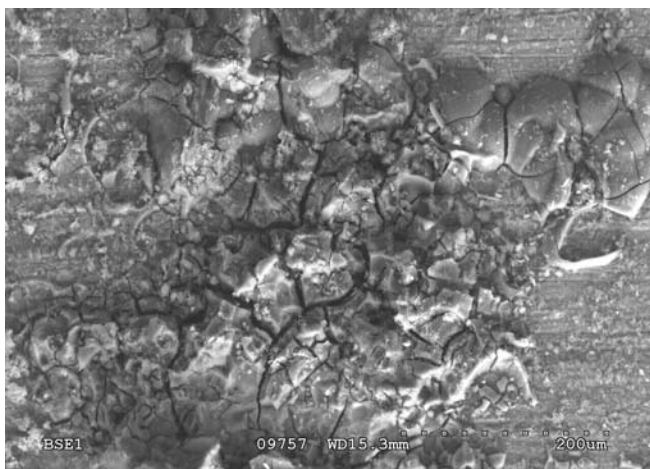
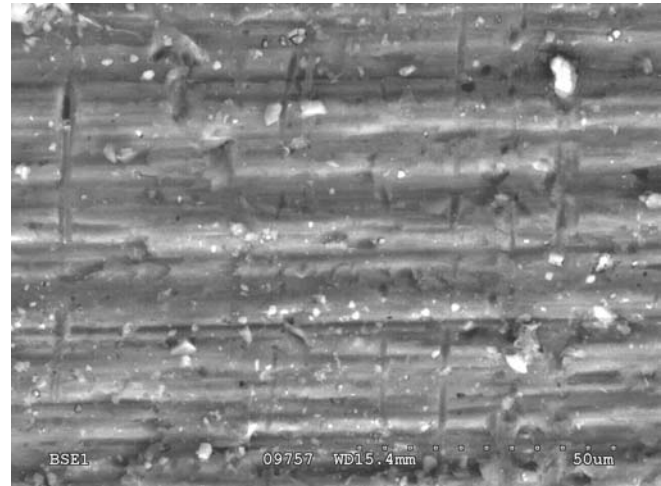
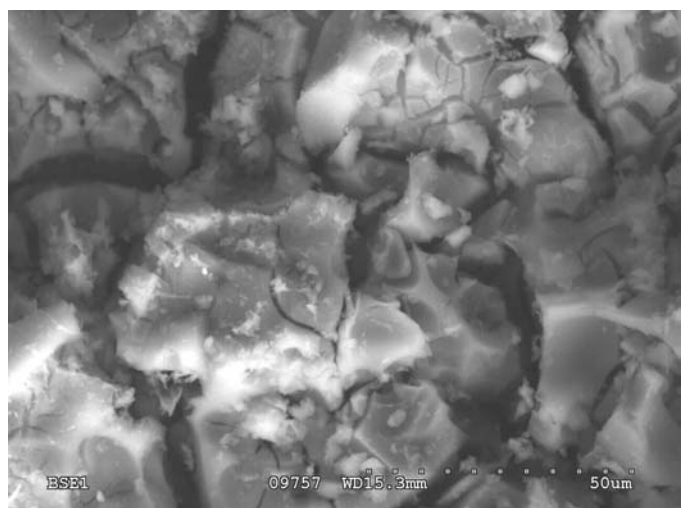


Figure 27
Higher magnification view at Location B, as illustrated in Figure 24. Adherent corrosion products are evident at this area. (SEM 200X)

Figure 28
Higher magnification view at the center of Figure 27, showing adherent amorphous deposits. (SEM 1000X)



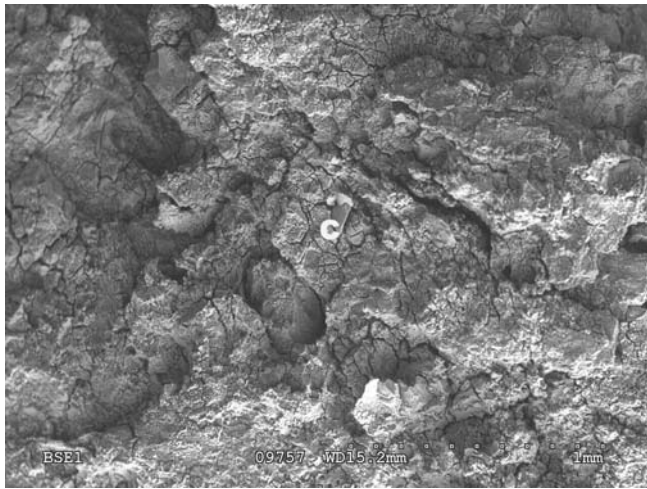


Figure 29
Scanning Electron Micrographs showing an additional corroded region of Sample 3. This area was identified as Location C, and contains adherent amorphous deposits. (SEM 50X)

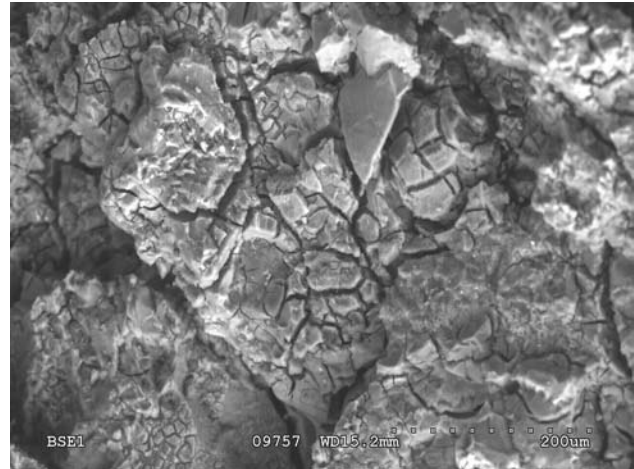


Figure 30
Higher magnification view at the center of Figure 29, showing adherent amorphous deposits. (SEM 200X)

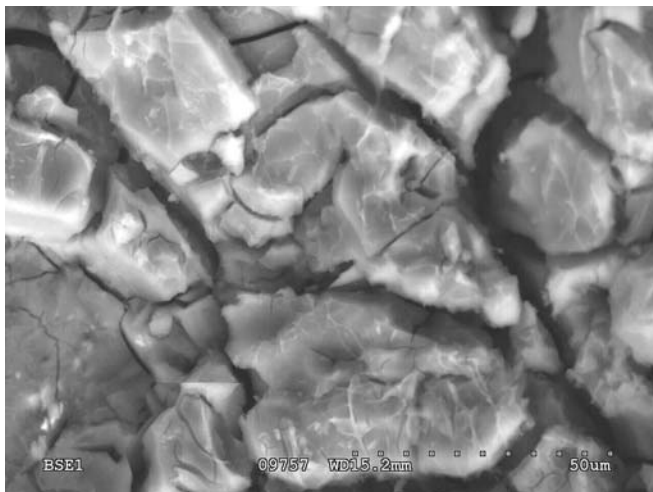


Figure 31
Higher magnification view at the center of Figure 30, showing deposits. (SEM 1000X)



Figure 32
Scanning electron micrograph showing an additional corroded region of Sample 3. This area was identified as Location D. (SEM 50X)

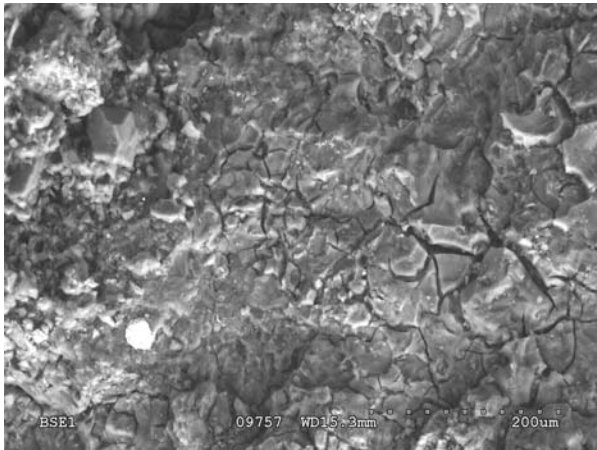


Figure 33
Higher Magnification view at the center of Figure 32, showing adherent amorphous deposits. (SEM 200X)

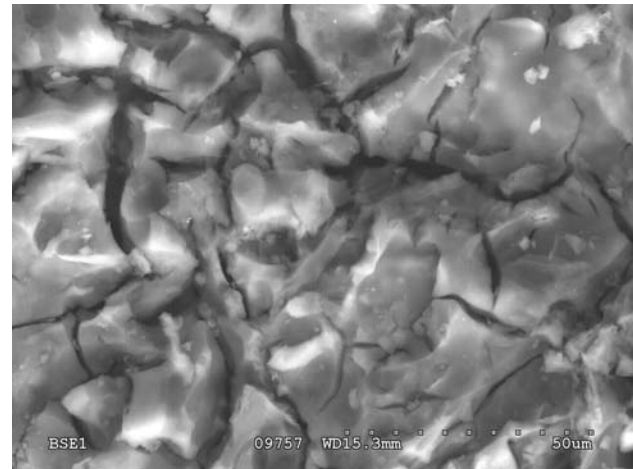


Figure 34
Higher magnification view at the center of Figure 33, showing deposits. (SEM 1000X)

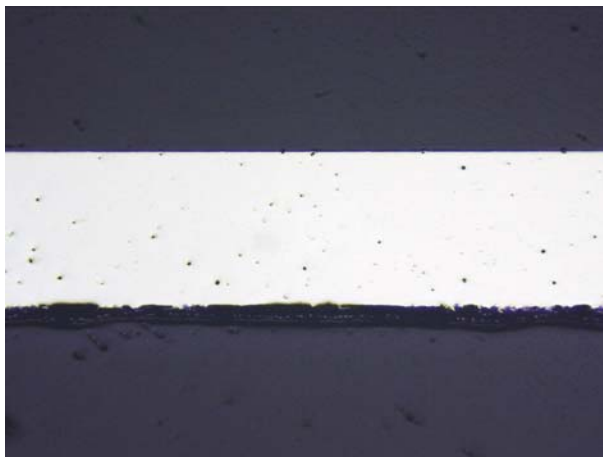


Figure 35
Transverse metallographic cross section through Sample 1, showing small amounts of porosity in the core. Unetched. (15X)

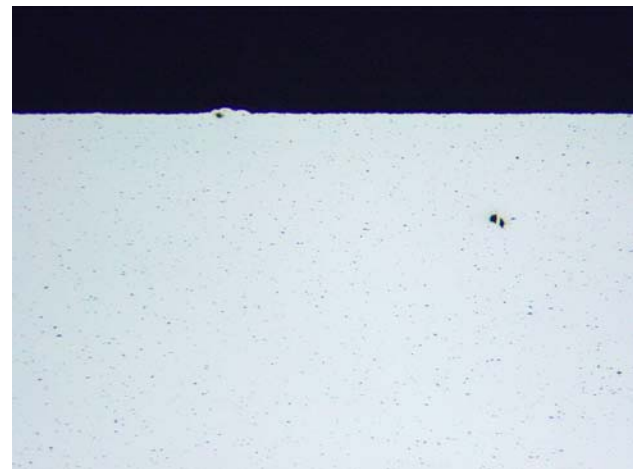


Figure 36
Higher magnification view at the surface profile of Sample 1, showing small amounts of porosity, with iron/chromium-rich phases in the core. Unetched. (100X)



Figure 37
Higher magnification view within the core of Sample 1, showing iron/chromium-rich phases. Unetched. (500X)

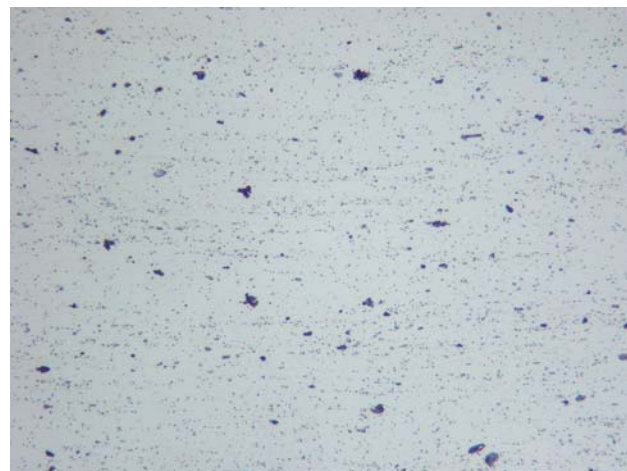


Figure 38
The core of Sample 1 is shown after etching, and contains magnesium silicide particles and iron/chromium-rich phases. Keller's reagent. (500X)

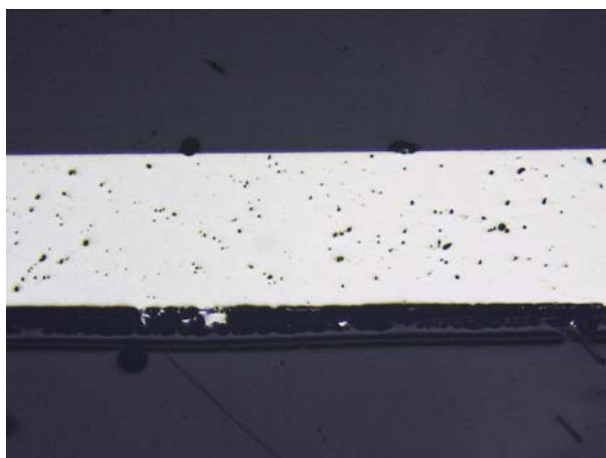


Figure 39
Transverse metallographic cross section through Sample 2, showing severe porosity. Unetched. (15X)

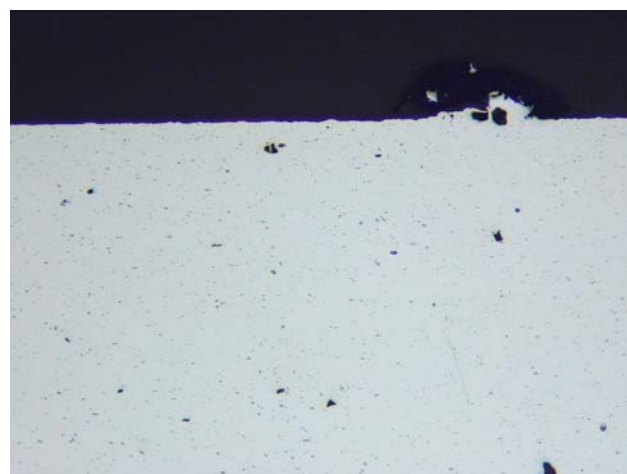


Figure 40
Higher magnification view of the surface profile of Sample 2, showing porosity at the surface and within the core. Iron/chromium-rich phases are also evident. Unetched. (100X)

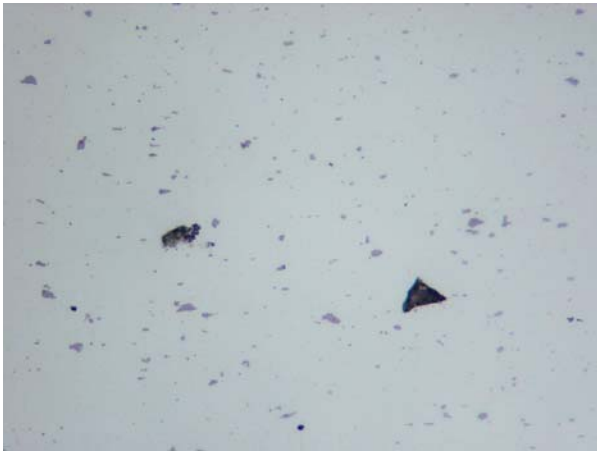


Figure 41
Higher magnification view of the core area of Sample 2, showing iron/chromium-rich phases and some porosity. Unetched. (500X)

Figure 42
The core of Sample 2 is shown after etching, and contains magnesium silicide particles and iron/chromium-rich phases. Keller's reagent. (500X)

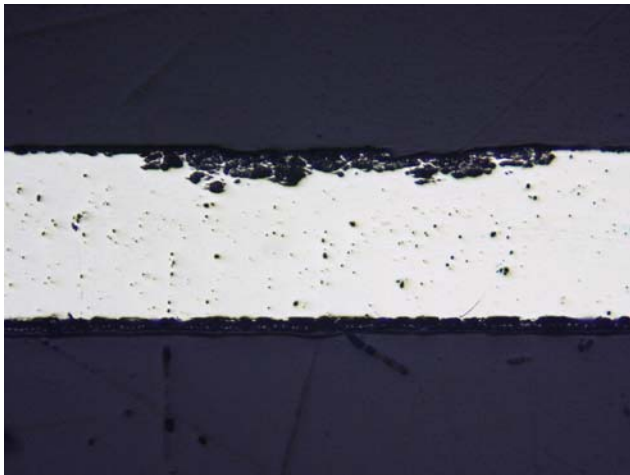
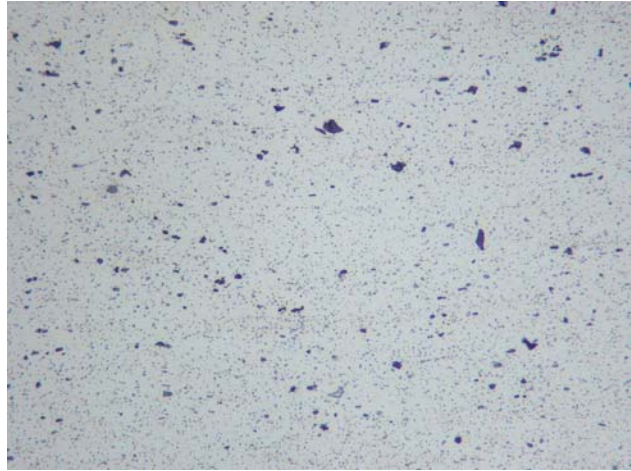


Figure 43
Transverse metallographic cross section through the corroded area of Sample 3, showing severe porosity in the core, with corrosion along the surface. Unetched. (15X)

Figure 44
Higher magnification view within the corroded region along the surface of Sample 3. This area exhibits features that are consistent with severe corrosion of wrought aluminum. Unetched. (100X)

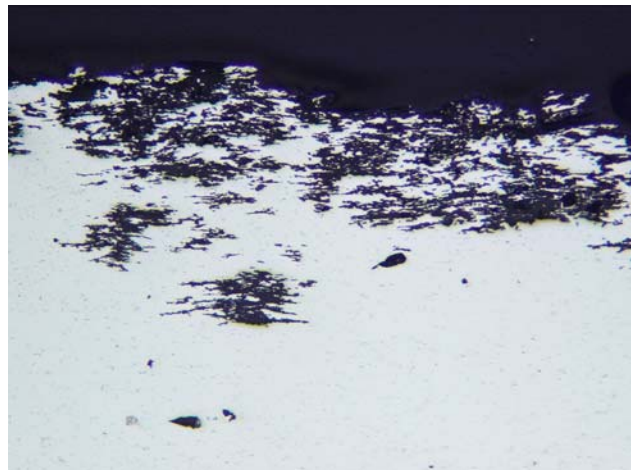




Figure 45
Higher magnification view of the microstructure near the surface of Sample 3, showing iron/chromium-rich phases and features that are consistent with corrosion. Unetched. (500X)

Figure 46
The region within the corroded area of Sample 3 is shown after etching, where magnesium silicide particles are present along with iron/chromium-rich phases. Keller's reagent. (500X)

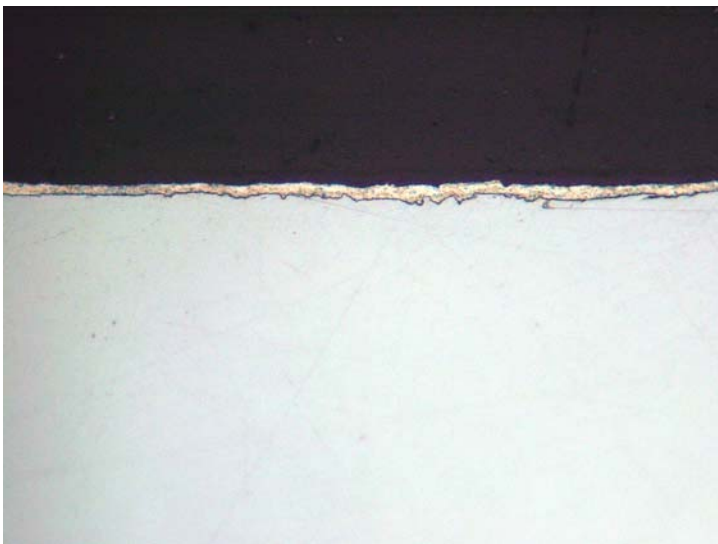
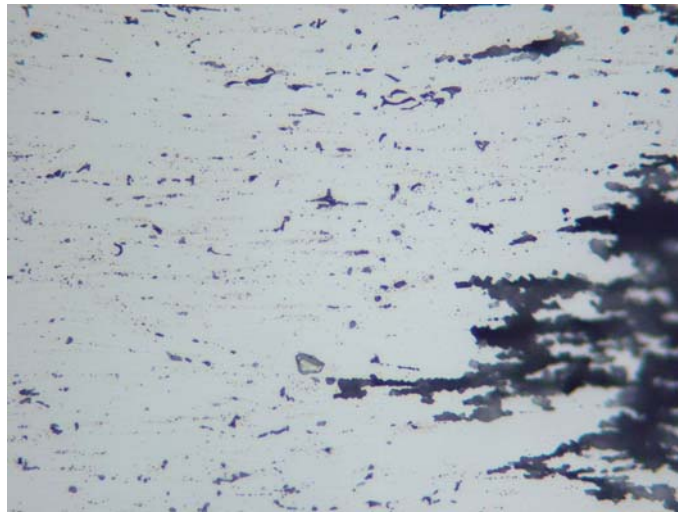
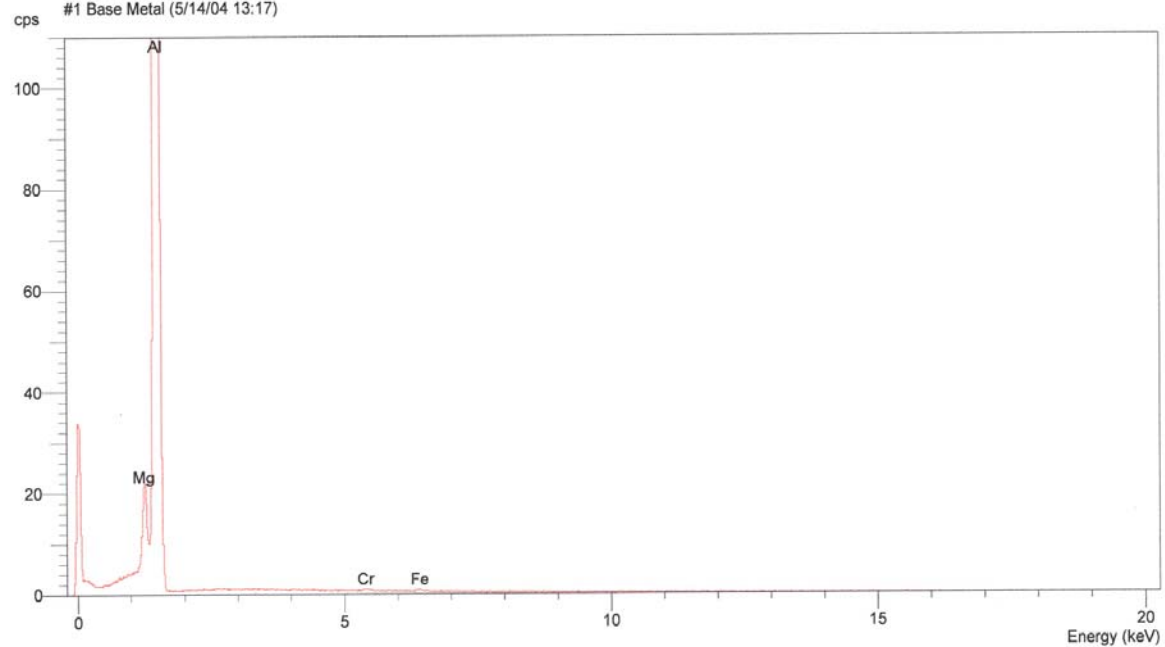
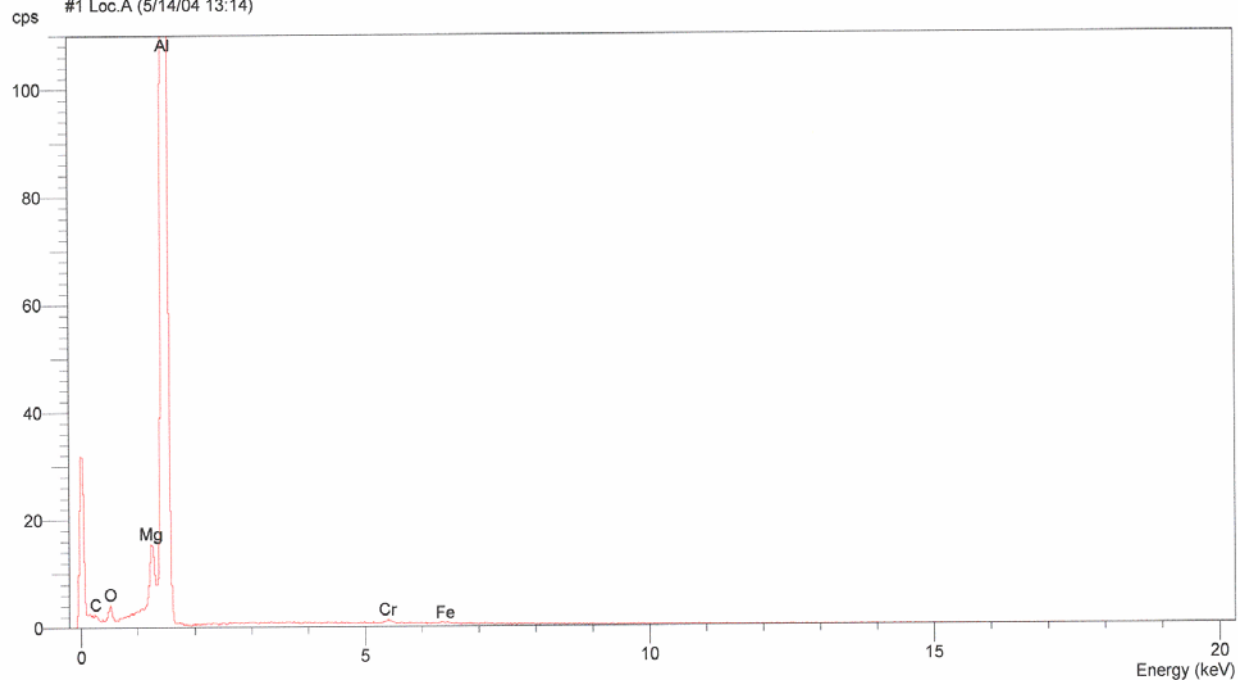


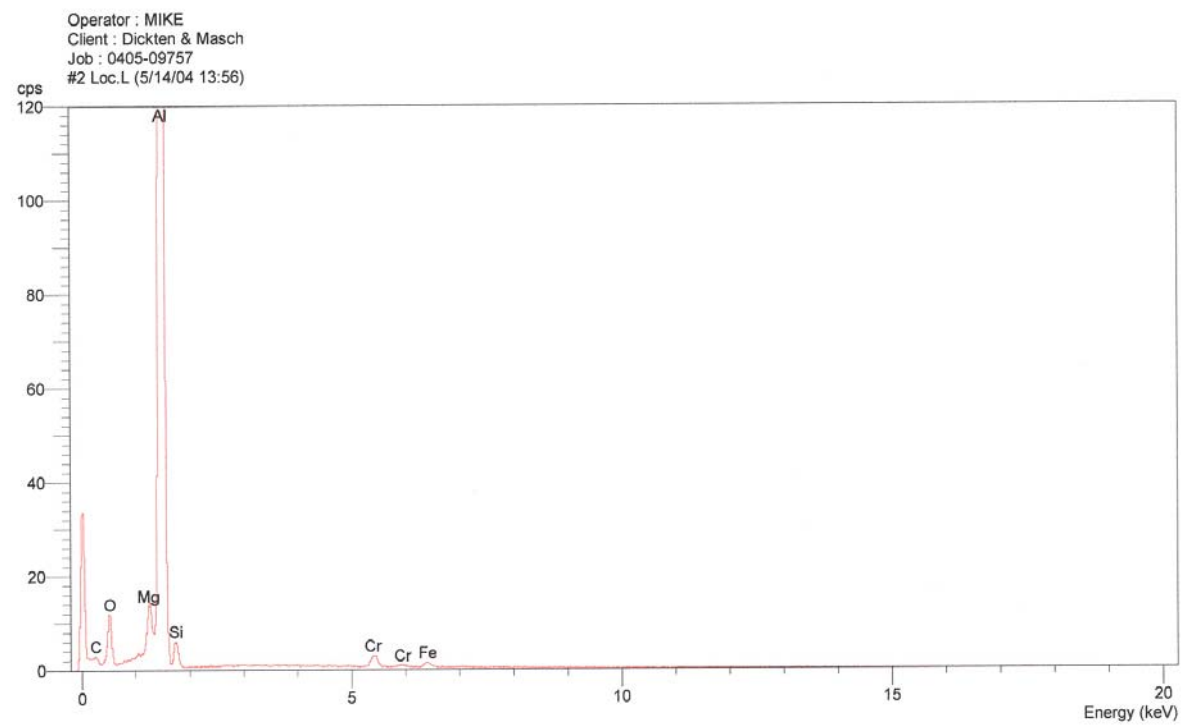
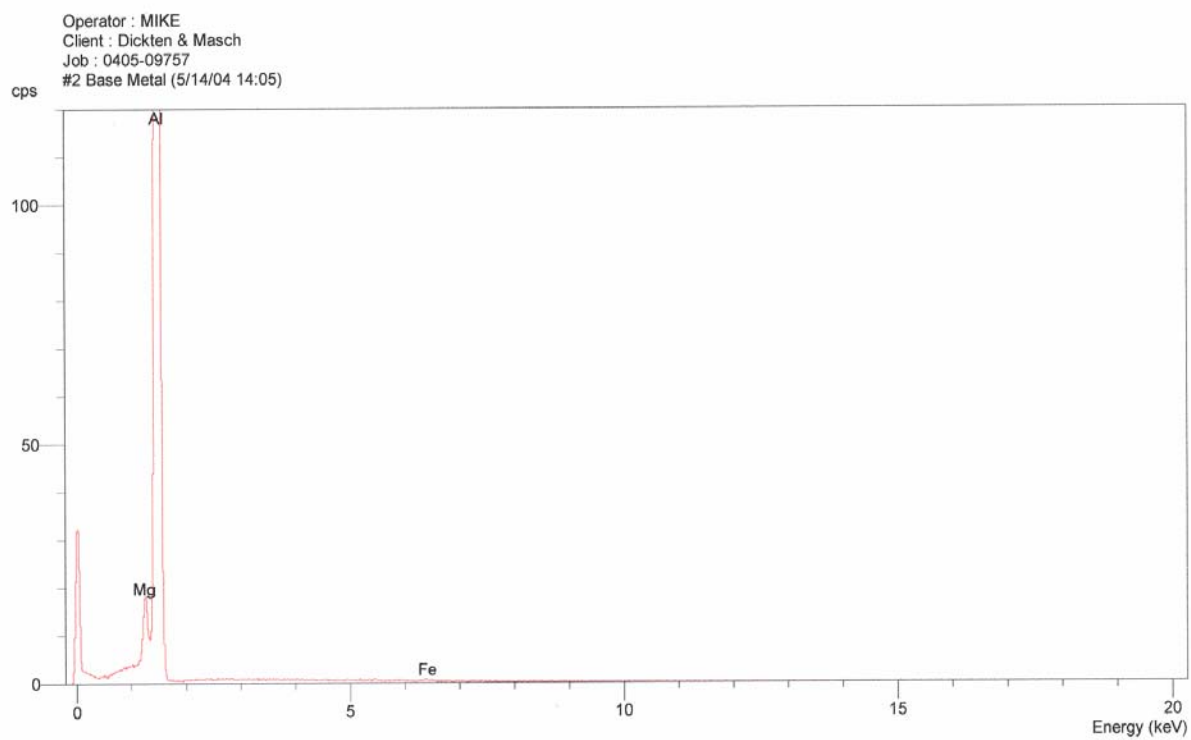
Figure 47
The surface profile of the lag screw, identified as Sample 6, shows a zinc layer with a nominal thickness of 0.16 mils. Unetched. (500X)

Operator : MIKE
Client : Dickten & Masch
Job : 0405-09757
#1 Base Metal (5/14/04 13:17)

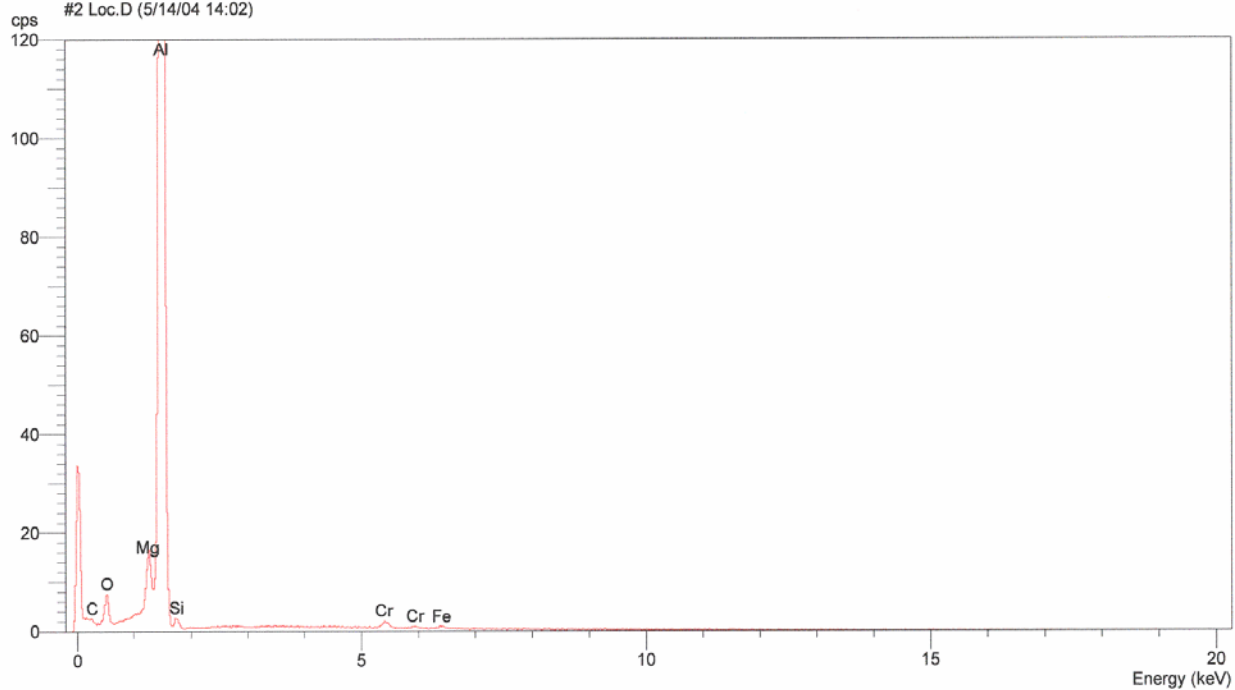


Operator : MIKE
Client : Dickten & Masch
Job : 0405-09757
#1 Loc.A (5/14/04 13:14)

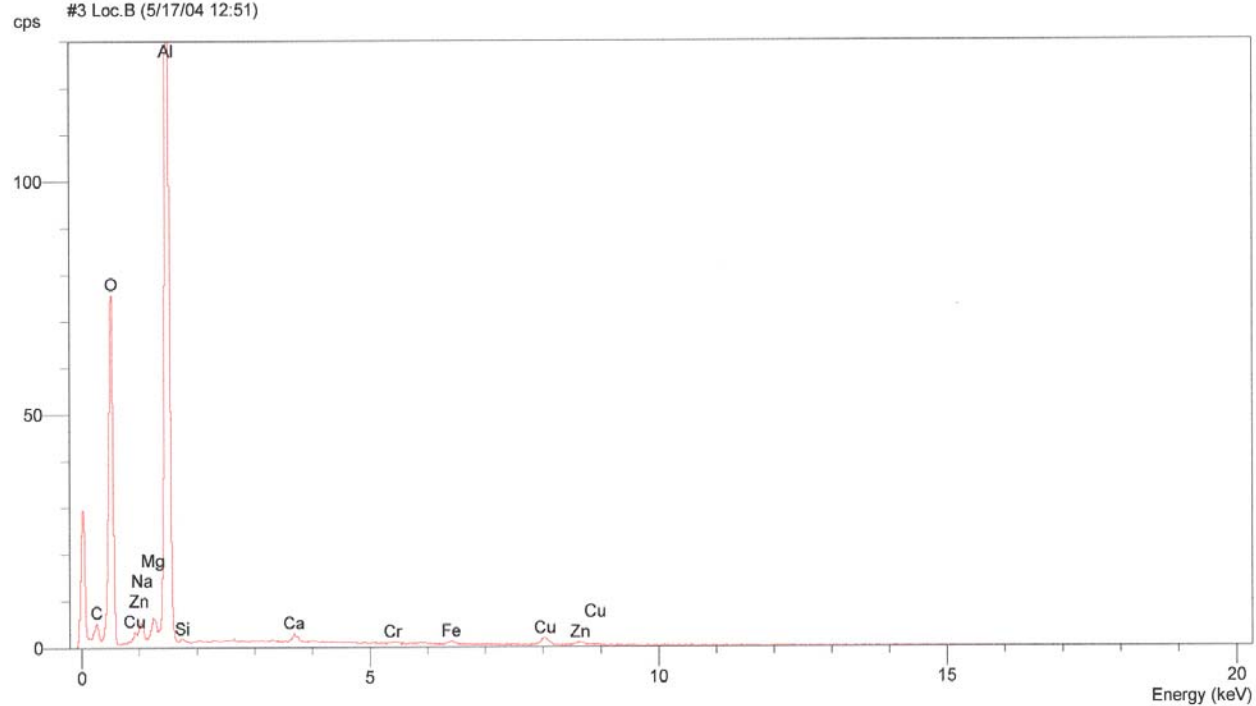


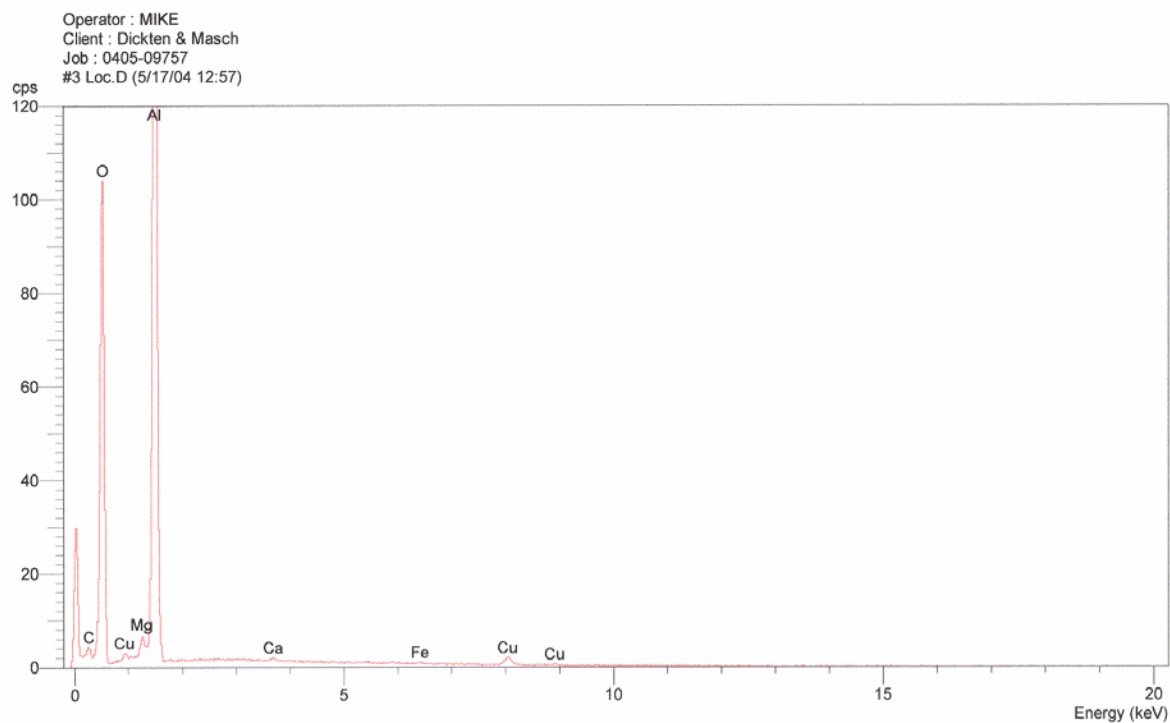
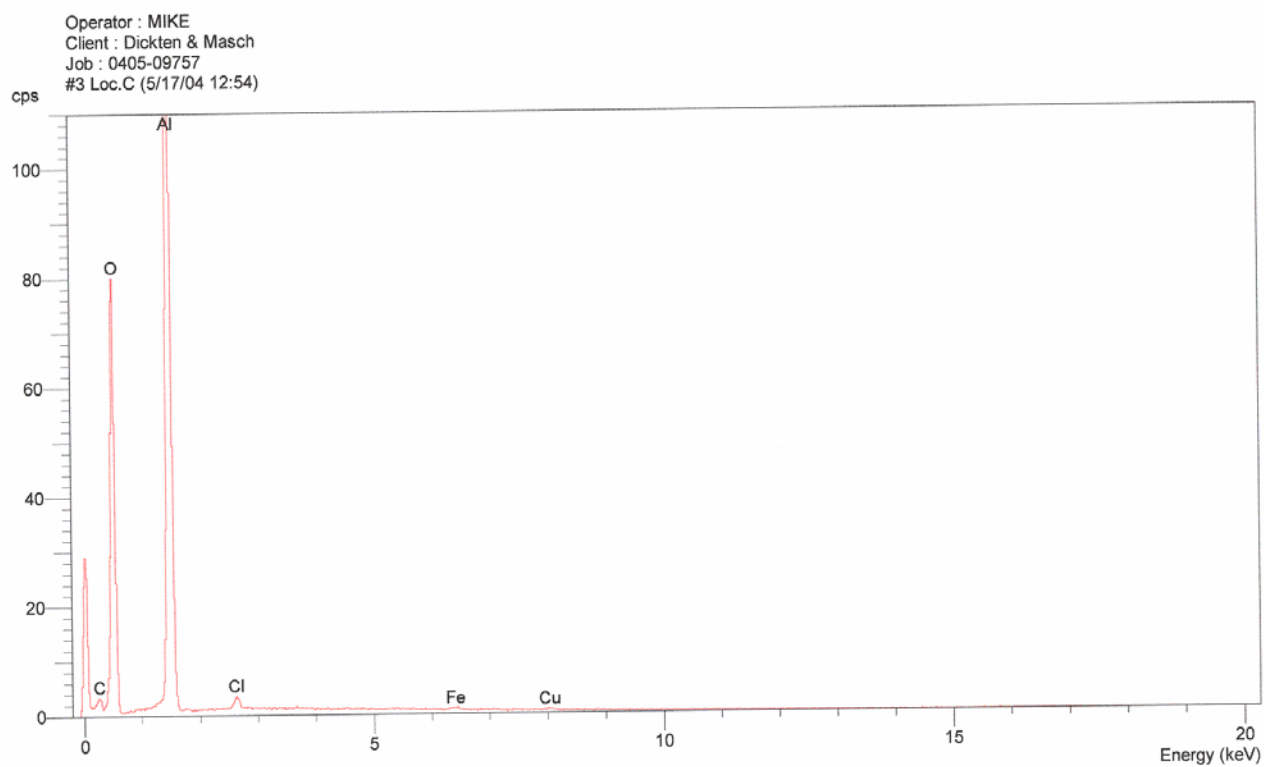


Operator : MIKE
Client : Dickten & Masch
Job : 0405-09757
#2 Loc.D (5/14/04 14:02)

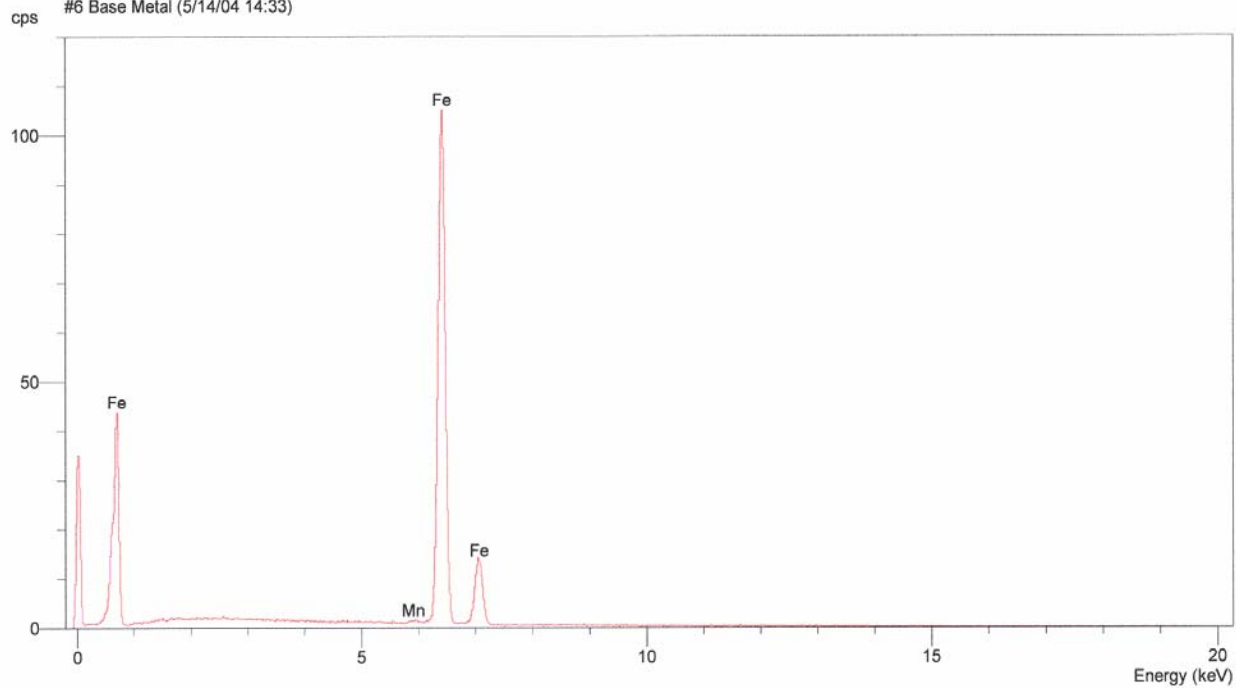


Operator : MIKE
Client : Dickten & Masch
Job : 0405-09757
#3 Loc.B (5/17/04 12:51)





Operator : MIKE
Client : Dickten & Masch
Job : 0405-09757
#6 Base Metal (5/14/04 14:33)



Operator : MIKE
Client : Dickten & Masch
Job : 0405-09757
#6 Surface (5/14/04 14:38)

